Tipping points in the climate system

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What are climate tipping points?

A climate tipping point is where a small amount of extra climate forcing, usually linked to global warming – for example, greenhouse gas forcing – triggers a qualitative change in part of the climate system. Change may already be underway in that sub-system, but it becomes abrupt and/or irreversible beyond the tipping point. This is because tipping points occur when reinforcing (positive) feedbacks within a system take over from stabilising (negative) feedbacks and propel change from one state to another. The transition triggered by a tipping point can be fast or slow from a human perspective: its rate depends on the processes propelling it. The climate system is comprised of multiple sub-systems, feedbacks, and non-linear relationships – which gives it the potential to exhibit multiple tipping points at different scales. Large parts of the climate system that can pass tipping points are called 'tipping elements' (Lenton *et al*., 2008). Under rare conditions it is possible for the whole climate system to pass a tipping point. Historical examples include the onset of ice-age cycles ~2.5 million years ago and their switch in frequency ~1 million years ago.

Where are the tipping elements?

Potential tipping elements in the Earth's climate system (Lenton *et al*., 2008) can be identified from the paleoclimate record, from scientific understanding of relevant feedbacks, and from climate model projections. The most policy-relevant tipping elements are those at risk of passing tipping points this century due to human activities, which result in significant damages. Policy-relevant tipping elements have been identified in three types of climate sub-system: the cryosphere, circulation of the atmosphere/ocean, and the biosphere. These systems are already changing, but that change could become abrupt and/or irreversible past a tipping point. Cryosphere tipping points include irreversible meltdown of the Greenland ice sheet, and irreversible grounding line retreat of the West Antarctic ice sheet, or of Wilkes Basin in East Antarctica. Circulation tipping points include collapse of the oceanic Atlantic Meridional Overturning Circulation (AMOC), disruption of the West African monsoon, and of the South Asian/Indian summer monsoon. Biosphere tipping points include large-scale dieback of the Amazon rainforest and of boreal forests. More localised tipping points are associated with permafrost collapse and degradation of tropical coral reefs. As research continues new tipping elements are sometimes discovered and others may be struck off the list.

How close are we to tipping points?

Tipping points are challenging to predict because of their non-linearity: change appears to be happening smoothly and then suddenly it becomes abrupt and/or irreversible. However, useful information on the proximity of different tipping points has been gleaned from past and present observational data and from models. Resulting scientific assessment of the likelihood of tipping points has changed over time. When first considered by the IPCC (Intergovernmental Panel on Climate Change) 20 years ago, tipping points were only judged to become likely with unmitigated global warming of >4 degC above preindustrial (Lenton *et al*., 2019). Now they are assessed to have significant probability at today's warming level of >1 degC, rising to high probability above 2 degC global warming (IPCC, 2018; Lenton *et al*., 2019). Observational evidence suggests part of the West Antarctic ice sheet may already be experiencing the onset of an irreversible ice sheet instability (IPCC, 2019). Accelerating changes in the Wilkes Basin, the Greenland ice sheet, the Amazon rainforest, the AMOC, and coral reefs may signal approaching tipping points – but could also be due to accelerating forcing. To reduce this uncertainty and deduce whether negative feedbacks are getting weaker (consistent with an approaching tipping point) requires studying how a system responds to perturbations, not just its mean state. This can provide early warning signals of an approaching tipping point, as recently demonstrated for the Greenland ice sheet (Boers and Rypdal, 2021).

What are the impacts of crossing tipping points?

Crossing climate tipping points can accelerate some of the most damaging impacts of climate change and trigger new impacts. Climate tipping point impacts are typically large, often irreversible, and unfold at different rates. Collapse of monsoon systems can happen fast and could devastate food production for hundreds of millions of people. Loss of the Greenland or West Antarctic ice sheets takes centuries but together could eventually add around 10m to global sea level, forcing the relocation of major population centres. Tipping point impacts are relatively under-assessed compared to other climate change impacts. The best studied is a collapse of the AMOC, which would fundamentally change European climate, raise sea levels in the North Atlantic region by up to a metre, and disrupt monsoons around the tropics including in West Africa and India. As this example highlights, tipping elements can interact in a way that passing one makes triggering another more likely (Lenton *et al*., 2019). Indeed, Arctic sea ice retreat and associated warming is already accelerating melt of the Greenland ice sheet, and that meltwater is in turn contributing to weakening the AMOC. Such coupled, cascading changes increase the risk posed by tipping points (Lenton *et al*., 2019).

What can we do about this risk?

To minimise the risk of passing multiple, interacting tipping points, we need to meet the Paris Agreement goal to limit global warming to 'well below 2 degC'. This means reaching global 'net zero' greenhouse gas emissions by around the middle of this century. To help achieve this, the risk from tipping points needs to be included in economic analysis of climate change to capture the true social cost of carbon emissions: it increases that social cost by up to an order of magnitude (Cai *et al*., 2016). If we fail to avoid tipping points, radical adaptations may be needed – for example, retreat from coastal megacities and massive resettlement of people.

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